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# Power factor correction of an electrical drive system based on multiphase machines

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**Abstract**—This paper deals with the energy efficiency improvement of an electrical drive which can be used both in wind energy conversion or motor drive applications. A power factor (PF) control scheme is presented allowing energy efficiency enhancement and optimization in high power variable-speed drives based on multiphase machines. Thus, the double-star induction machine is taken, as an example of multiphase machines, to introduce the principle of the study presented in this paper. In fact, the purpose of this paper is to maintain the PF of the power-winding, of the double star induction machine, in vicinity of unity whatever the drive operating point. Also, this control scheme can be generalized for several kinds of multiphase machines.

**Keywords**— Double fed induction machine; energy efficiency; multiphase machine; power factor control (PFC).

## I. INTRODUCTION

Nowadays, a great interest for multiphase electrical machines is in progress, both for renewable energy applications or energy electromechanical conversion. Multiphase machine signify a machine with more than three phases in the stator side. So, the number of phases can be used as an additional degree of freedom to improve reliability, efficiency and optimization of the overall system. Such improvements can be easily demonstrated considering the torque ripples reduction, power segmentation and fault-tolerance capability [1-3].

As most of drive systems are dedicated to variable-speed and variable-load operations, this leads to operating point variation and consequently to PF variation. It is shown in several works that switching losses in static converters are PF depending in case of use of the so called discontinuous PWM techniques (DPWM) [4-7]. So, the switching losses can be significantly reduced using DPWM techniques at high PF values and this contributes strongly to energy efficiency improvement. Moreover in high power applications, having low converter losses is essential to maintain thermal limits.

This paper proposes an improved power factor (PF) control scheme in high power variable-speed drives based on multiphase machines. This control scheme is inspired from that of the double-fed induction machine where both stator and rotor are fed by static inverters in order to compensate reactive power and therefore ensure a unity power factor operation [8], [9]. Moreover, this scheme can be used in case of generator or motor operations and generalized for all kinds of multiphase machines.

An example of a multiphase machine is multi-star machine and particularly the double star induction machine (DSIM). Thus, the DSIM is taken as an example to introduce the principle of the study presented in this paper. So, the first star can be used as control winding (CW) to compensate the reactive power while the second one acts as power winding (PW) which provides the necessary active power, as shown in Fig. 1. Hence, the purpose of this paper is to maintain the PF of the power-winding, of the double star induction machine, in vicinity of unity whatever the drive operating point, allowing DPWM techniques selection. Also, this control scheme can be generalized for several kinds of multiphase machines.

## II. SYSTEM DESCRIPTION

The system is composed of a DSIM, where its two sets of three-phase windings share the same stator magnetic core and spatially phase shifted by 30 electrical degrees. Also, the two sets are identical and symmetrical with the two neutrals being isolated. Each set of stator winding is fed by a three-phase voltage source inverter (VSI). The rotor is identical to that of a three-phase squirrel cage induction machine. Depending on the control strategy, the DSIM can be considered as an asymmetrical six-phase machine, and therefore the Park model is obtained by applying an appropriate transformation matrix which leads to three sub-models completely decoupled [2], [10]. In this paper the DSIM is considered as the combination of two three-phase machines sharing the same magnetic circuit and the usual Park transformation is applied for each three-phase set [11].

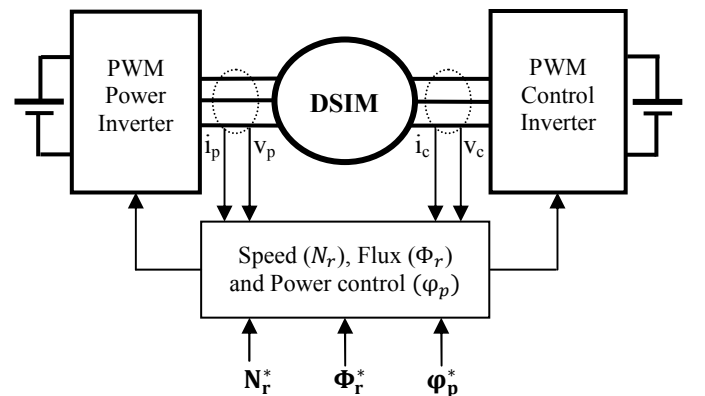


Fig. 1. DSIM PF control principle scheme.

### III. MACHINE MODELING

Based on the usual simplification assumptions and considering the DSIM as the combination of two three-phase machines sharing the same magnetic circuit, the usual Park transformation is applied for each three-phase winding. Thus, the DSIM model is decomposed into two main sub-models noted (ds<sub>1</sub>-qs<sub>1</sub>) and (ds<sub>2</sub>-qs<sub>2</sub>) for the stator side and one sub-model noted (dr-qr) for the rotor side. All sub-models are expressed in the synchronous reference frame.

The stator voltage sub-model (ds<sub>1</sub>-qs<sub>1</sub>) is written as:

$$\begin{cases} V_{sd1} = R_s I_{sd1} + \frac{d\phi_{sd1}}{dt} - \omega_s \phi_{sq1} \\ V_{sq1} = R_s I_{sq1} + \frac{d\phi_{sq1}}{dt} + \omega_s \phi_{sd1} \end{cases} \quad (1)$$

The stator voltage sub-model (ds<sub>2</sub>-qs<sub>2</sub>) is written as:

$$\begin{cases} V_{sd2} = R_s I_{sd2} + \frac{d\phi_{sd2}}{dt} - \omega_s \phi_{sq2} \\ V_{sq2} = R_s I_{sq2} + \frac{d\phi_{sq2}}{dt} + \omega_s \phi_{sd2} \end{cases} \quad (2)$$

The rotor voltage sub-model (dr-qr) is written as:

$$\begin{cases} V_{rd} = 0 = R_r I_{rd} + \frac{d\phi_{rd}}{dt} - \omega_r \phi_{rq} \\ V_{rq} = 0 = R_r I_{rq} + \frac{d\phi_{rq}}{dt} + \omega_r \phi_{rd} \end{cases} \quad (3)$$

The flux equations can be written as:

$$\begin{cases} \phi_{sd1} = L_s I_{sd1} + L_{ms} I_{sd2} + M I_{rd} \\ \phi_{sq1} = L_s I_{sq1} + L_{ms} I_{sq2} + M I_{rq} \end{cases} \quad (4)$$

$$\begin{cases} \phi_{sd2} = L_s I_{sd2} + L_{ms} I_{sd1} + M I_{rd} \\ \phi_{sq2} = L_s I_{sq2} + L_{ms} I_{sq1} + M I_{rq} \end{cases} \quad (5)$$

$$\begin{cases} \phi_{rd} = L_r I_{rd} + M(I_{sd1} + I_{sd2}) \\ \phi_{rq} = L_r I_{rq} + M(I_{sq1} + I_{sq2}) \end{cases} \quad (6)$$

The electromagnetic torque is as following:

$$T_e = p \frac{M}{L_r} [\phi_{rd}(I_{sq1} + I_{sq2}) - \phi_{rq}(I_{sd1} + I_{sd2})] \quad (7)$$

Because the two star's neutrals are isolated, the traditional homopolar components are neglected. All machine's parameters are defined in the appendix.

If the voltage equations (1), (2) and (3) of the DSIM are examined, they look-like those of two separate three-phase machines. But, the flux equations (4), (5) and (6) present coupling terms, because the two three-phase windings share the same magnetic circuit. In spite of these coupling terms, the control of the DSIM can be done exactly as the case of the three-phase machine.

### IV. DRIVE CONTROL

In this section the indirect field oriented control (IFOC) technique applied to the DSIM is presented firstly and then the proposed PF control scheme, based on IFOC principle, will be detailed.

In case of rotor flux orientation, its components are controlled to ensure the following condition:

$$\begin{cases} \phi_{rq} = 0 \\ \phi_{rd} = \phi_r \end{cases} \quad (8)$$

The DSIM control can be ensured via the stator current components by substituting (8) in (6) and eliminating the rotor current components from (4) and (5). This leads to the following flux expressions:

$$\begin{cases} \phi_{sd1} = \sigma_1 L_s I_{sd1} + \sigma_2 L_{ms} I_{sd2} + \frac{M}{L_r} \phi_r \\ \phi_{sq1} = \sigma_1 L_s I_{sq1} + \sigma_2 L_{ms} I_{sq2} \end{cases} \quad (9)$$

$$\begin{cases} \phi_{sd2} = \sigma_1 L_s I_{sd2} + \sigma_2 L_{ms} I_{sd1} + \frac{M}{L_r} \phi_r \\ \phi_{sq2} = \sigma_1 L_s I_{sq2} + \sigma_2 L_{ms} I_{sq1} \end{cases} \quad (10)$$

$$\begin{cases} I_{rd} = \frac{1}{L_r} (\phi_r - M(I_{sd1} + I_{sd2})) \\ I_{rq} = -\frac{M}{L_r} (I_{sq1} + I_{sq2}) \end{cases} \quad (11)$$

$$\text{With : } \sigma_1 = 1 - \frac{M^2}{L_s L_r} ; \sigma_2 = 1 - \frac{M^2}{L_{ms} L_r} ; T_r = \frac{R_r}{L_r}$$

Substituting (9), (10) and (11) in stator and rotor voltage equations (1), (2) and (3) provides the main expressions as following:

$$\begin{cases} V_{sd1} = R_s I_{sd1} + \sigma_1 L_s \frac{dI_{sd1}}{dt} + \frac{M}{L_r} \frac{d\Phi_r}{dt} - \omega_s \sigma_1 L_s I_{sq1} \\ \quad + \sigma_2 L_{ms} \frac{dI_{sd2}}{dt} - \omega_s \sigma_2 L_{ms} I_{sq2} \\ V_{sq1} = R_s I_{sq1} + \sigma_1 L_s \frac{dI_{sq1}}{dt} + \omega_s \frac{M}{L_r} \Phi_r + \omega_s \sigma L_s I_{sd1} \\ \quad + \sigma_2 L_{ms} \frac{dI_{sq2}}{dt} + \omega_s \sigma_2 L_{ms} I_{sd2} \end{cases} \quad (12)$$

$$\begin{cases} V_{sd2} = R_s I_{sd2} + \sigma_1 L_s \frac{dI_{sd2}}{dt} + \frac{M}{L_r} \frac{d\Phi_r}{dt} - \omega_s \sigma_1 L_s I_{sq2} \\ \quad + \sigma_2 L_{ms} \frac{dI_{sd1}}{dt} - \omega_s \sigma_2 L_{ms} I_{sq1} \\ V_{sq2} = R_s I_{sq2} + \sigma_1 L_s \frac{dI_{sq2}}{dt} + \omega_s \frac{M}{L_r} \Phi_r + \omega_s \sigma L_s I_{sd2} \\ \quad + \sigma_2 L_{ms} \frac{dI_{sq1}}{dt} + \omega_s \sigma_2 L_{ms} I_{sd1} \end{cases} \quad (12)$$

$$\begin{cases} M(I_{sd1} + I_{sd2}) = \Phi_r + T_r \frac{d\Phi_r}{dt} \\ \omega_r = \frac{(I_{sq1} + I_{sq2})}{T_r(I_{sd1} + I_{sd2})} \end{cases} \quad (13)$$

Taking into account the steady state operation, the rotor flux can be written as following:

$$\Phi_r = M(I_{sd1} + I_{sd2}) \quad (14)$$

Also, the torque equation (7) becomes:

$$T_e = p \frac{M}{L_r} \Phi_r (I_{sq1} + I_{sq2}) \quad (15)$$

Expressions (14) and (15) demonstrate the principle of IFOC control of DSIM and allow PF control as shown in next section.

## V. POWER FACTOR CORRECTION

While, the purpose of this paper is to maintain the PF in vicinity of unity whatever the drive operating point, this section exposes the principle of the proposed PF control technique. So, based on the IFOC scheme the simplest way to ensure a PF correction is to impose the following condition:

$$I_{sd2} = I_{sq1} = 0 \quad (16)$$

Equations (13), (14) and (15) become as follows:

$$\begin{cases} \Phi_r = M I_{sd1} \\ T_e = p \frac{M}{L_r} \Phi_r I_{sq2} \\ \omega_r = \frac{I_{sq2}}{T_r I_{sd1}} \end{cases} \quad (17)$$

Equation (17) shows that the rotor flux can be controlled by  $I_{sd1}$  current component which provides the required magnetizing reactive power, and the torque can be controlled by  $I_{sq2}$  component as well the active power. The active and reactive powers are given as follows:

$$\begin{cases} P_{s1} = V_{sd1} I_{sd1} + V_{sq1} I_{sq1} \\ Q_{s1} = V_{sq1} I_{sd1} - V_{sd1} I_{sq1} \end{cases} \quad (18)$$

$$\begin{cases} P_{s2} = V_{sd2} I_{sd2} + V_{sq2} I_{sq2} \\ Q_{s2} = V_{sq2} I_{sd2} - V_{sd2} I_{sq2} \end{cases} \quad (19)$$

According to (16) the relations (18) and (19) become:

$$\begin{cases} P_{s1} = V_{sd1} I_{sd1} \\ Q_{s1} = V_{sq1} I_{sd1} \end{cases} \quad (20)$$

$$\begin{cases} P_{s2} = V_{sq2} I_{sq2} \\ Q_{s2} = -V_{sd2} I_{sq2} \end{cases} \quad (21)$$

Expressions (20) and (21) show that also active and reactive powers can be controlled by  $I_{sd1}$  and  $I_{sq2}$  current components, as for rotor flux and torque.

In addition, the stator current components  $I_{sq1}$  and  $I_{sd2}$  offer another degree of freedom for more system control. Thus, based on the powers relations (18) and (19) the new current references  $I_{sd2}$  and  $I_{sq1}$  that allowing the cancellation of  $Q_{s2}$  and  $P_{s1}$  are as following:

$$\begin{cases} I_{sq1} = -\frac{V_{sd1} I_{sd1}}{V_{sq1}} \\ I_{sd2} = \frac{V_{sd2} I_{sq2}}{V_{sq2}} \end{cases} \quad (22)$$

Based on (22), PF control scheme can be chosen based on PF reference, as well a power control technique as DPC (Direct Power Control) can be implemented. While the aim of this paper is only to introduce the possibility of PF control principle in multiphase machines under IFOC, proper power control techniques are under studies and will be reported in a subsequent paper.

## VI. SIMULATION RESULTS

In order to demonstrate the effectiveness of the proposed scheme (Fig.1), some tests under IFOC are performed for both cases with and without PF control at the same conditions. Also, the simulation results presented in this section concern only the steady state operation. Thus, initially the motor is running at 716 rpm corresponding to its rated speed without a load torque, and then low load torques of 5 Nm and 10 Nm are applied at instants  $t=0.3$  s and  $t=0.5$  s respectively as shown in Fig.2 (the traced torque is multiplied by a coefficient equal 20, for purpose of presentation). These load torque values are selected in order to allow a low PF operation. Also, in the next sections a detailed comparison focuses only on the operating point corresponding to the lowest PF value under a load torque of 5 Nm.

### a) IFOC of DSIM

The main simulation results corresponding to normal operation of the DSIM under IFOC, where the two stator winding sets provide equal powers, are shown in Fig. 3. Accordingly for the operating point corresponding to load torque of 5 Nm, the rotor flux and speed (torque) control loops lead to  $I_{sd1} = I_{sd2} = 3A$  corresponding to the nominal flux, and  $I_{sq1} = I_{sq2} = 1.65A$  equivalent to the load torque, as shown in Fig. 3-(a) and (b). As a result, the active powers are  $P_{s1} = P_{s2} = 225W$  as well the reactive powers are  $Q_{s1} = Q_{s2} = 885VAR$ , as shown in Fig. 3-(c). Hence, the corresponding PF value is low and equal to 0.25 (Fig. 3-(d)), equivalent to a load angle of  $\varphi_{s1} = \varphi_{s2} = 75^\circ$  (Fig. 3-(e)-(f)), for both CW and PW as well as the total PF.

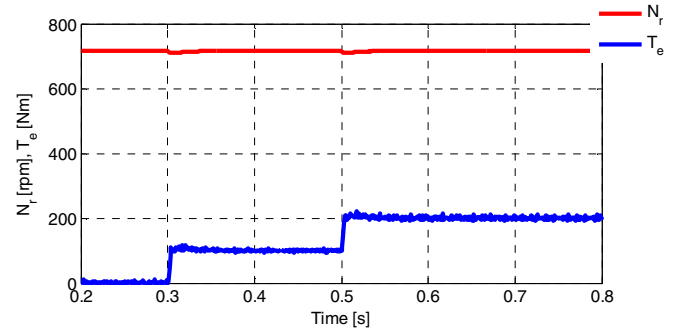


Fig. 2. Motor speed and torque curves.

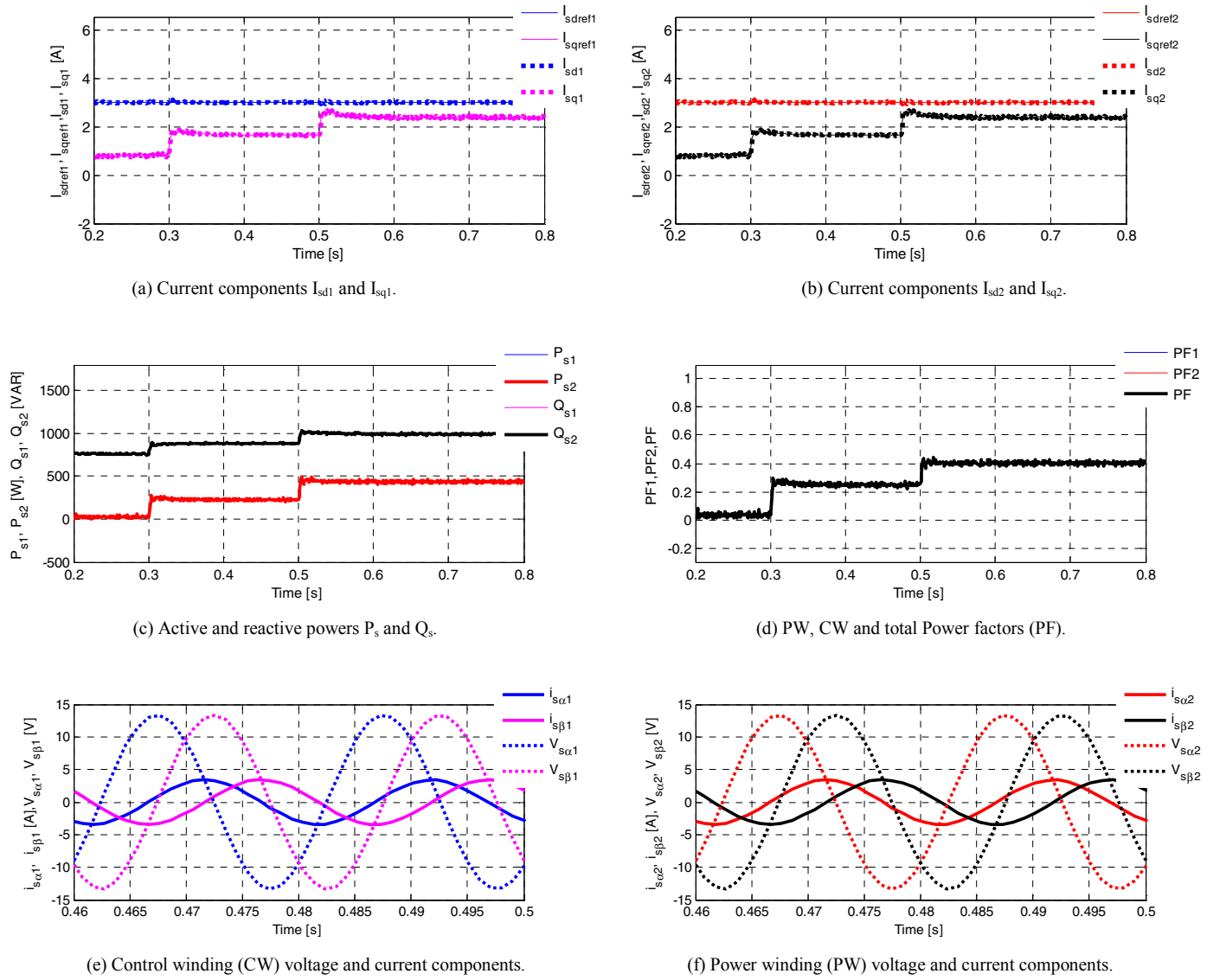
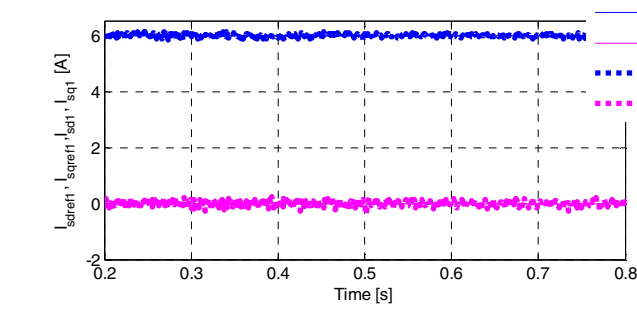


Fig. 3. Simulation results of IFOC of DSIM.

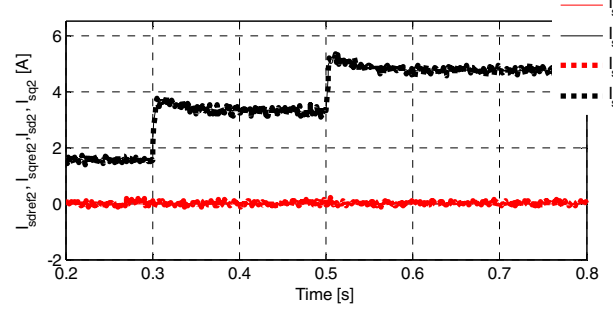
#### b) PF correction with IFOC

The PF presented in Fig.3 is a low for both stator windings and this leads to additional power losses, especially inverter switching losses [6]. Furthermore, having two separate stator windings constitutes an additional freedom degree which can be used to manage the total power between those windings. Thereby, the CW is used to improve the PF of the PW and therefore the drive total efficiency. Accordingly, Fig.4 shows the simulation results of PF correction with the new current structure and simulation conditions as for the previous case. As a result, the main variables become  $I_{sd1} = 6A$  for the rotor

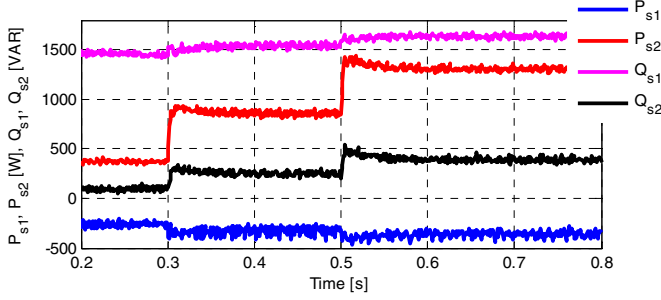
flux, and  $I_{sq2} = 3.3A$  for the load torque (Fig. 4-(a)-(b)). Also, the active powers are  $P_{s1} = -320W$  for the CW and  $P_{s2} = 860W$  for the PW, as well the reactive powers are  $Q_{s1} = 1540VAR$  for the CW and  $Q_{s2} = 250VAR$  for the PW. So, it can be remarked that the PW practically supplies all the active power with a slight amount of reactive power and the CW provides the necessary reactive power. Consequently, the PF of the PW is forced to be equal to  $PF_2 = 0.96$  in the vicinity of unity and different from that of the CW which is equal to  $PF_1 = -0.2$ , whereas the total PF is slightly improved and equal to  $PF = 0.285$ .



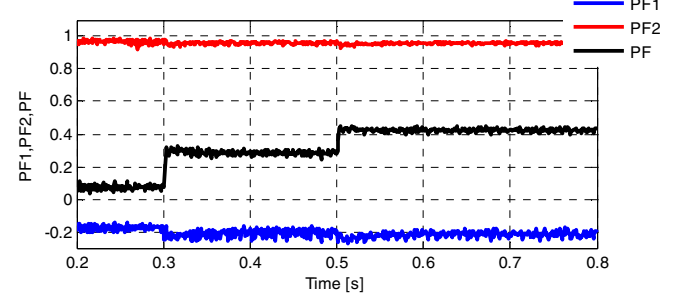
(a) Current components  $I_{sd1}$  and  $I_{sq1}$ .



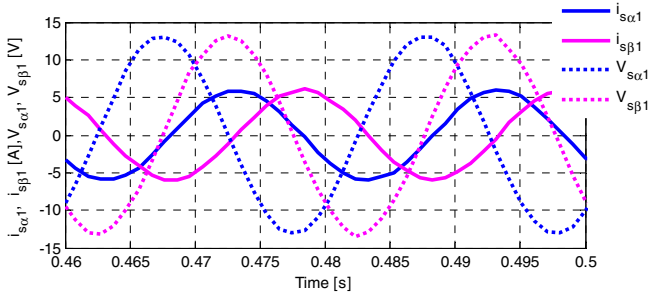
(b) Current components  $I_{sd2}$  and  $I_{sq2}$ .



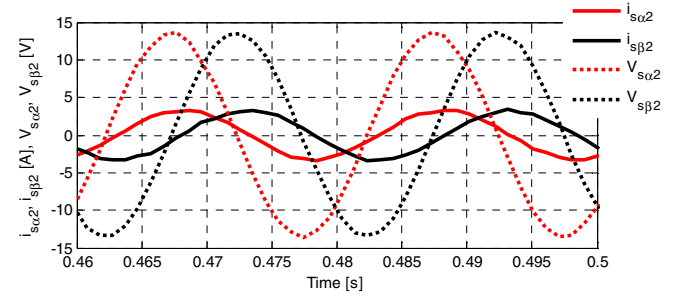
(c) Active and reactive powers  $P_s$  and  $Q_s$ .



(d) PW, CW and total Power factor (PF).



(e) Control winding (CW) voltage and current components.



(f) Power winding (PW) voltage and current components.

Fig. 4. Simulation results of PFC under IFOC.

### c) Active and reactive power control

The new current references  $I_{sq1}$  and  $I_{sd2}$ , calculated using (22), are introduced into the simulation program of the drive control scheme of Fig.1. Also, the nominal flux is maintained by the current component  $I_{sd1} = 6A$ , while the other variables become  $I_{sq2} = 2.1A$  for the load torque,  $I_{sq1} = 1.2A$  and  $I_{sd2} = -0.6A$  for the new power control current references (Fig. 5-(a)-(b)). Hence, the main active and reactive power components are  $P_{s2} = 520W$  for the PW and  $Q_{s1} = 1520VAR$  for the CW, respectively, whereas the extra power components  $P_{s1}$  and  $Q_{s2}$  are concealed (Fig. 5-(c)). Consequently, as shown in Fig. 5-(e) and (f) the CW load angle is kept  $\varphi_{s1} = 90^\circ$  equivalent to  $PF_1 = 0$  and the PW load angle is forced to be  $\varphi_{s2} = 0^\circ$  allowing unity PF with  $PF_2 = 1$ , moreover the total drive PF equals 0.32 demonstrating an improvement ratio of 7%.

## VII. CONCLUSION

In this paper the principle of PF correction in multiphase machines is presented and applied to a DSIM operating under IFOC. Simulation results are shown a successful decoupled power control and the PF of the PW is maintained equal to unity whatever the drive operating point with a significant improvement of the total drive PF.

This scheme is suitable for as most of drive systems based on multiphase machines dedicated to variable-speed and variable-load operations, and consequently to PF variation. While the aim of this paper is only to introduce the possibility of PF correction principle in multiphase machines under IFOC, switching losses evaluation is under studies and will be reported in a subsequent paper.

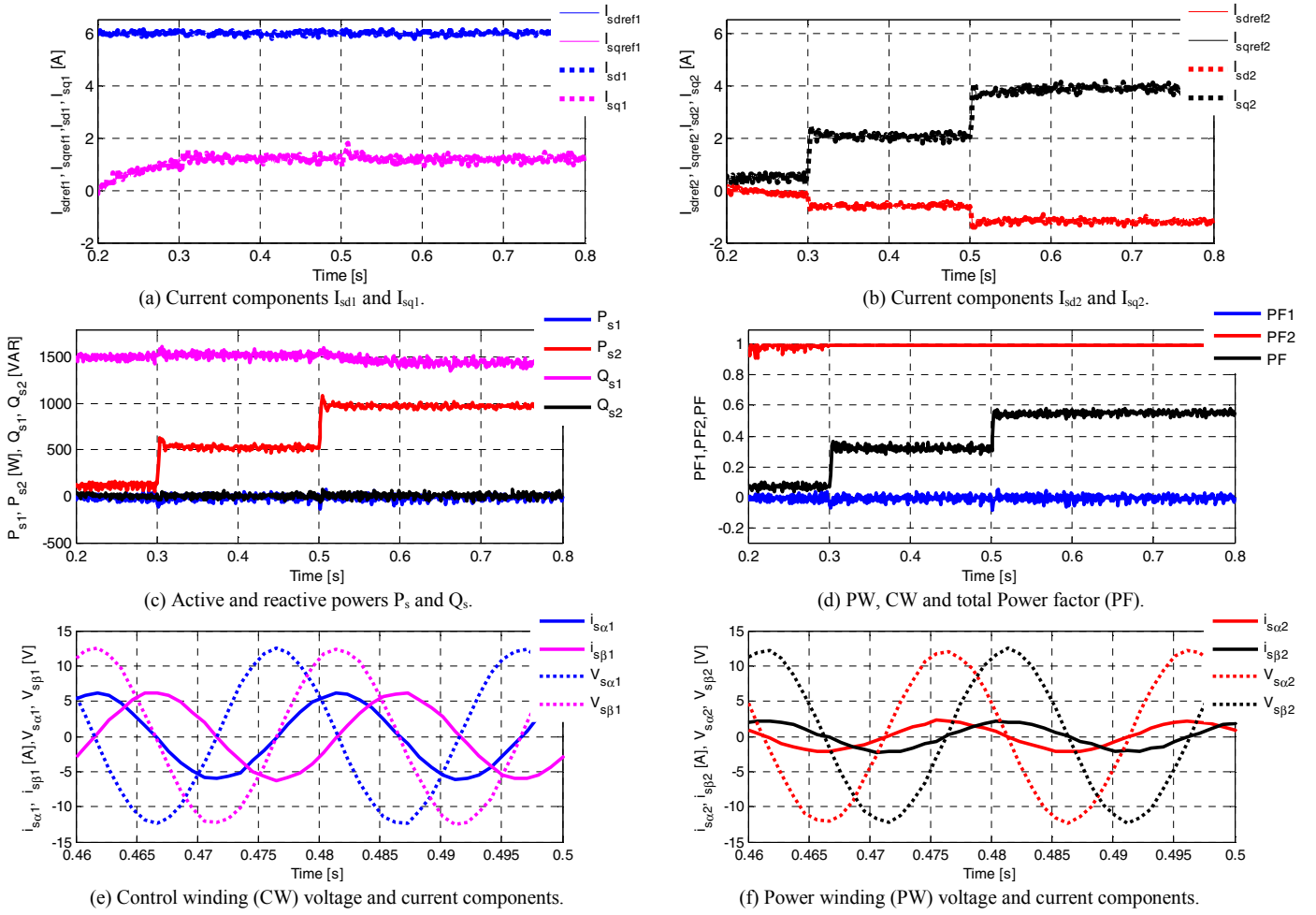


Fig. 5. Simulation results of PFC under active and reactive power control.

#### APPENDIX

TABLE I: Double Star Induction Machine parameters

Quantity	Symbol and magnitude
Rated Power	$P_n = 5.5 \text{ kW}$
Rated voltage	$V_n = 220 \text{ V}$
Rated current	$I_n = 6 \text{ A}$
Rated speed	$N_n = 950 \text{ rpm}$
Number of poles	$2 \cdot p = 6$
Rated Frequency	$f = 50 \text{ Hz}$
Stator resistance	$R_s = 2.03 \Omega$
Rotor resistance	$R_r = 3 \Omega$
Stator inductance	$L_s = 0.215 \text{ H}$
Rotor inductance	$L_r = 0.215 \text{ H}$
Mutual inductance	$M = 0.2 \text{ H}$
Moment of inertia	$J = 0.06 \text{ kg.m}^2$
Coefficient of viscous friction	$k_f = 0.006 \text{ N.m.s/rad}$

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